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2.	Patent application number *(The Patent Office will fill in this part)*	0216018.2 11 JUL 2002
3.	Full name, address and postcode of the or of each applicant *(underline all surnames)*	Willett International Limited 3 Cronin Road 11JUL02 E732455-1 D01070 Weldon South Industrial Estate P01/7700 0.00-0216018.2 Corby NN18 8AQ
	Patents ADP number *(if you know it)*	825810003
	If the applicant is a corporate body, give the country/state of its incorporation	United Kingdom
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6.	If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number			

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8.	Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:* *a) any applicant named in part 3 is not an inventor, or* *b) there is an inventor who is not named as an applicant, or* *c) any named applicant is a corporate body.* *See note (d))*	YES

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11. I/We request the grant of a patent on the basis of this application.

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TITLE: DEVICE AND METHOD OF OPERATION

The present invention relates to a device, notably a high speed solenoid type valve and to an ink jet printer containing such a valve; and to a method of operating an ink jet print head utilising that valve.

BACKGROUND TO THE INVENTION:

Ink jet printers are non-contact printers in which droplets of ink are ejected from one or more nozzles in a print head. The ejected droplets are projected onto a substrate moving relative to the print head and progressively build up a printed image on the substrate from the dots of ink applied to the substrate. For convenience, the present invention will be described in terms of a substrate which moves with respect to a stationary print head. However, the invention may also be applied to printers in which the print head moves with respect to a stationary substrate.

One form of ink jet printer comprises a source of ink under pressure, typically a reservoir or bottle of ink which is pressurised to from 0.1 to 3 bar, notably about 1 bar. The pressure is created, for example, by pressurising the air space above the ink in the bottle or reservoir. The ink is fed to a nozzle orifice in a print head through which it is ejected as a series of droplets onto the surface of the substrate. The print head typically comprises a row of such nozzle orifices arranged transversely to the direction of travel of the substrate.

The flow of ink through each nozzle orifice is controlled by a solenoid valve. Typically, such a valve comprises an electromagnetic plunger journalled for axial movement within an axially extending electric coil. The distal end of the plunger is located within a valve head chamber through which ink flows from the reservoir to the nozzle orifice. When current is fed through the coil, this generates a magnetic field which acts on the plunger to move it axially and thus open, or shut, the inlet to a bore or conduit to the nozzle orifice. Typically, the magnetic field acts to retract the plunger against the bias of a coil spring to create a flow path between the valve head chamber and the nozzle orifice. When the electric current no longer flows in the coil, the magnetic field ceases and the plunger returns under the bias of the spring to seat against sealing ribs, lips or other means located at or around the inlet to the bore or conduit to the nozzle orifice so as to close the flow path to the nozzle orifice. Typically, a plurality of nozzle orifices are formed as a row in a plate, the nozzle plate, and each nozzle orifice is served by a bore through the plate connected to the solenoid valve. Droplets of ink are ejected independently from one or more of the nozzle orifices upon actuation of the valve controlling the flow of ink to that nozzle orifice. Typically, the nozzle orifice is provided as the distal end of a bore in a jewel nozzle which is seated into the outlet end of a bore through the nozzle plate.

The valves are fed with ink from the reservoir via a manifold which serves to split and even the ink flow to

each of the valves. The row of nozzle orifices is typically aligned transversely to the direction of travel of the substrate, so that simultaneous operation of the valves will cause a row of ink dots to be printed on the substrate. The valves are operated so as to deposit dots of ink upon the substrate at the desired locations on the substrate to build up the elements of a five, seven, eight or more dot raster image on the substrate. By suitable sequencing of the opening of the various valves serving the nozzles, an alphanumeric or other image can be formed on the substrate to print a date, product batch code, logo, bar code or other image on the substrate. If desired, several nozzle plates can be combined in an array so as to print a wider image on the substrate and/or to achieve close printing of the dots on the substrate by staggering the nozzle plates with respect to one another.

For convenience, the term drop on demand printer will be used to denote in general such types of ink jet printer, the term nozzle orifice is used to denote the aperture through which the ink droplet is ejected, the term nozzle bore will be used herein to denote the bore connecting the valve head chamber with the nozzle orifice, and the term print head will be used to denote an assembly having one or more nozzle orifices and associated valves.

For a given nozzle orifice diameter, the size of the printed dot can readily be altered by varying the duration for which the valve is held open, and hence the amount of ink that allowed to flow through the nozzle orifice. The form of the image which is printed can readily be altered

by varying the sequence of operation of the valves in the print head so that droplets are ejected from the appropriate nozzles in the appropriate sequence to form the desired image. Such alterations of the images and the dot sizes can readily be controlled by a computer or microprocessor operating under an appropriate program or operating system.

Such drop on demand printers are widely available commercially and find widespread use in printing a wide range of both visible and non-visible machine-readable images on a wide range of substrates. The print heads can project the droplets from the nozzle orifices for a flight path length of 10 to 25 mms or more, allowing the print head to be located adjacent to a line of travelling articles in a production or packaging without the print head fouling the articles.

However, as the relative speed of travel between the print head and the substrate increases, a point is reached at which the valve cannot be operated at sufficient speed to eject droplets at sufficient frequency to form the desired image without creating some distortion. Typically, the limit for the speed of operation of solenoid valves in current use in an ink jet printer head is less that 1000Hz. With increasing pressure on manufacturers to increase through put from a given production or packaging line, there is an increasing need to be able to print the dots onto the substrate at rates greater than this.

In an alternative form of ink jet printer, known as an

impulse jet printer, a piezoelectric crystal or other transducer is applied to or forms part of a wall of an ink jet chamber having an ink inlet and having an ink outlet nozzle bore to a nozzle orifice. When a voltage is applied to the transducer, the transducer expands or flexes and causes a change in the volume of the ink jet chamber. This causes a droplet of ink to be ejected from the chamber and to exit through the nozzle orifice via the nozzle bore. The transducer can be caused to flex at very high frequencies by electronic control of the frequency of the electrical pulses applied to the transducer, so that such a print head can apply dots at frequencies up to 15kHz or more. However, the volume of ink ejected through the nozzle orifice is dependent upon the extent of flexing of the transducer. This can be varied by varying the amplitude of the electric pulse applied to the transducer. However, each type of transducer operates consistently only within a narrow percentage, typically plus or minus 10%, of the optimum operating pulse amplitude, so that only a limited range of dot sizes can be achieved with a commercially available impulse jet printer. In order to increase the printed dot size it is necessary to print successive dots overlapping with one another. This limits the number of applications a given impulse jet head can be used for. Furthermore, such impulse jet heads project the droplet for only a small flight path distance, typically no more than 6 mms, since the pressure generated to expel the droplet of ink from the nozzle orifice is small. The pressure cannot be increased beyond a low threshold level, since the ink is held within the nozzle bore by the surface tension forces at the meniscus of the ink at the

nozzle orifice. Also, the nozzle bore and nozzle orifice are formed in a thin wall of the chamber and the nozzle bore typically has a length to diameter ratio of less than 0.5:1. As a result the directionality of the flight path of the ejected droplets is reduced as compared to a drop on demand printer where the nozzle bore in a jewel nozzle typically has a length to diameter ratio of 10:1 or more. Scatter of the droplets on the substrate increases if the flight path of the droplets is larger than about 2 mms for an impulse jet printer. This further limits the application of such impulse jet printers.

In a further type of ink jet printer known as a continuous ink jet printer, a charged jet of ink is ejected from a nozzle. This jet is broken up into individual charged droplets which are then steered towards the desired location on a substrate by applying varying electric voltages to deflection electrodes located adjacent the flight path of the individual charged droplets. Whilst such a printer can form droplets at high frequencies and can project the individual droplets for distances of 5 to 15 cms, such printers are complex and costly to construct and operate.

International Patent Application No PCT/SE97/01007 describes a solenoid type valve for a drop on demand ink jet printer which is claimed to be capable of operating at frequencies of up to 3kHz. Such a valve incorporates light weight components so as to reduce the mass of the plunger and hence its inertia. This enables the plunger to accelerate and decelerate rapidly at each extreme of

its travel within the coil. To achieve this reduction in mass, the plunger is formed from two components, one made from an electromagnetic material so that it can be caused to move by the magnetic field generated by the coil, and a second lightweight plastic component for the distal end of the plunger. Such construction is complex and expensive. Furthermore, we have found that a drop on demand print head incorporating such a valve design does not print acceptable images. For example, at high frequencies of operation of the valve, the printed dots are uneven and there are many small satellite dots around each of the primary dots printed by the print head.

There thus still exists a need for a print head which is simple and yet can operate consistently at dot generation frequencies in excess of 1 Khz to generate uniformly sized droplets over a wide range of printed dot sizes using a wide range of inks or other fluids.

We have now devised a form of solenoid valve which can be operated at speeds of up to 8kHz or more and yet print uniformly sized droplets over a wide range of dot sizes and operating frequencies. Such a valve enables drop on demand technology to be used in high speed applications for which an impulse jet or continuous jet print head had hitherto been considered the only technically viable form of print head. A print head incorporating the valve of the invention can achieve the accuracy of placement of the printed dots and the long flight path of the droplets from the nozzle orifice to the surface of the substrate usually only achieved by slow speed drop on demand print heads.

Surprisingly, the valve of the invention is capable of printing accurate droplets over a wide range of sizes and frequencies without significant satellite droplet formation. The valve of the invention can be produced to a consistent performance and the movement of the plunger within the coil can readily be controlled by regulating the shape of the current pulse applied to the coil using software to optimise print quality. This is to be contrasted with conventional drop on demand printers where the computer is used only to regulate the open time of the valve and to relate the timing and sequence of operation of the valve to the image which is to be produced.

Furthermore, the design of the valve of the invention readily lends itself to manufacture as an array of valves, each serving one of a plurality of nozzles in a single nozzle plate. This enables the nozzle plate and associated structure of the valve to be produced as a unitary construction with greater accuracy than where individual valves and jewel nozzles are used. A print head incorporating an array of nozzles and valves can be made to more consistent standards of performance than hitherto.

Furthermore, a print head incorporating the present invention can be made more compact than one using conventional valves. This enables small dots to be printed at closer spacing than hitherto could be achieved with a drop on demand printer.

SUMMARY OF THE INVENTION:

Accordingly, the present invention provides a valve mechanism for controlling the flow of fluid therethrough, which mechanism comprises a plunger member journalled for axial reciprocation between a rest and an operative position within an electric coil under the influence of a magnetic field generated by that coil when an electric current passes through the coil, the distal end of the plunger extending into a valve head chamber having an outlet nozzle bore, the reciprocation of the plunger being adapted to open or close a fluid flow path from the valve head chamber through that bore, characterised in that:

a. the plunger is of a unitary construction and is made from an electromagnetically soft material having a saturation flux density greater than 1.5 Tesla, preferably about 1.6 to 2.2 Tesla or more; and

b. the nozzle bore leading from the valve head chamber to the nozzle orifice has a length to diameter ratio of less than 8:1, preferably from 0.5:1 to 5:1, notably from 1:1 to 3:1, especially 1:1 to 2:1.

Preferably the material from which the plunger is made also has a coercivity of less than about 100 ampere per metre, notably less than 50, for example about 25 amperes per metre; and a relative magnetic permeability in excess of 10,000, preferably in excess of 50,000, for example about 75 to 90,000.

The term magnetically soft is used herein to denote that the material loses the magnetic field induced in it by the coil when the current in the coil ceases, in contrast to a permanent magnet which retains its magnetism. For convenience, the terms distal and proximal will be used herein to denote that portion of a component which is located downstream and upstream respectively with respect to the flow of ink or other fluid through the valve.

We have found that the use of the specified materials for the plunger overcomes many of the problems associated with the use of the conventional stainless steel plunger materials, for example that sold under the trade mark Carpenter 430F or RF, which have saturation flux densities of less than about 1.4 Tesla, coercivities of about from 120 to 560 A/m and permeabilities of less than about 3,000. We have found that the conventional materials generate excessive heat energy when reciprocated at frequencies of 1 Khz. The use of materials having high magnetic flux saturation densities enables the plunger to respond rapidly to changes in the magnetic field generated by the coil without the generation of excessive heat. With the preferred materials, the low coercivity of the plunger material also aids the rapid rise and fall of the induced magnetic field within the plunger under the influence of the field generated as a current is passed through the coil at low applied coil currents. This, coupled with the high permeability of the material, enables a high magnetic drive force to be generated rapidly between the coil and the plunger. As a result, the plunger can be accelerated rapidly by the coil without

the need to apply high drive currents to the coil, typically in excess of 20 amperes, as hitherto considered necessary. This again reduces the heat energy which is generated as the plunger is moved by the coil. However, it may be possible to use a material of construction which has a coercivity and/or relative permeability outside the preferred ranges to achieve satisfactory results if the saturation flux density is sufficiently high.

The low coercivity also permits a reverse magnetic force to be generated rapidly by reversing the direction of the current in the coil. This reversed force can be used to slow down the movement of the plunger as it reaches either or both extremes of its travel. Such magnetic braking may be used in place of or in conjunction with the bias spring conventionally used to return the plunger to its rest position. The magnetic braking can also be used to reduce the impact of the plunger as its seats against the inlet to the nozzle bore. This not only increases the operating life of the plunger and seal components, but also reduces satellite droplet formation as the valve closes. However, it will usually be preferred that the valve mechanism of the invention also comprises a pre-tensioned spring member to bias the plunger against the magnetic field generated by the coil so as to return the plunger to its rest position when an electric current is not applied to the coil.

Furthermore, we have found that the valve of the invention can be held in the open position for prolonged periods to print continuous lines on the substrate which have a

length equivalent to at least three individual printed dots. With conventional solenoid valves, it has been considered necessary to pulse the current to the coil so as to form overlapping dots of ink on the substrate. In practice this often leads to the valves burning out due to the high currents applied to the coil to move the plunger from its initial rest position into the valve fully open position. We have found that the amplitude of the current flowing through the coil required to hold the plunger in the valve open position is surprisingly much less, typically 80 to 50% less, than the current required to move the plunger initially away from its rest position. By applying a current pulse which has an initial amplitude sufficient to move the plunger from its rest position to the valve open position and then reducing this amplitude to a lower value for the remainder of the pulse, it is possible to hold the valve open for prolonged periods so as to print lines of ink on the substrate.

Accordingly, the present invention also provides a method for operating the solenoid valve of a drop on demand ink jet printer, notably a valve of the invention, to print a line of ink upon a substrate which line has a length equivalent to at least three individual printed dots, characterised in that the plunger is held in the valve open position by applying a current to the coil of the valve which current has an amplitude of less than 50% of that required to move the plunger initially from its rest position.

We have found that these benefits are achieved to a

remarkable extent when the plunger is of low mass, for example when the plunger has a diameter of less than 2.5 mms, notably about 1 mm, and has a length to diameter ratio of more than 3:1, preferably from about 5:1 to 10:1. As result, in a preferred embodiment, the invention provides a compact, light weight solenoid valve characterised in that the plunger has a diameter of less than 2.5 mms, notably about 1 mm, and has a length to diameter ratio of more than 3:1, preferably from about 5:1 to 10:1. Preferably, the plunger has a unitary construction and is made from a material having the magnetic properties defined above for the valve of the invention.

The valves of the invention are capable of operation at frequencies in excess of 2 Khz, notably up to 8 Khz. This is within the operating range of a conventional continuous jet printer, so that the valve of the invention enables a drop on demand ink jet printer to print images on a fast moving substrate with reduced distortion of the printed image as compared to a conventional drop on demand printer. Such a valve can be made very compact so that an array of the valves can serve one or more rows of nozzle bores in a nozzle plate to provide a compact print head with high print resolution.

Surprisingly, we have further found that where the valve of the invention is used in a drop on demand ink jet printer, problems due to drying out of the ink within the nozzle bore are reduced. In ink jet printers, drying out of the ink through loss of the solvent or carrier medium

for the ink when the printer or nozzle is at rest and ink is not flowing through the nozzle bore causes the formation of solid deposits in the bore. In a conventional drop on demand or impulse jet printer, when the valve or transducer of the print head is actuated again to eject a droplet from the nozzle orifice after such a rest period, this deposit impedes the flow of ink through the nozzle bore. As a result, the initial droplets ejected from the nozzle orifice are deformed and of uneven size. This effect is accentuated in impulse jet printers where the length of the bore is very short. Surprisingly, we have found that, despite having a lower length to diameter ratio of the nozzle bore as compared to a drop on demand printer, the valve of the invention recovers more rapidly than a conventional drop on demand ink jet printer valve after a rest period. This is effect is surprisingly enhanced when the L:D ratio of the nozzle bore is reduced to below 3:1, notably to from 1:1 to 2:1. As a result, problems due to initial droplet malformation after a rest period of the valve of the invention are reduced.

We believe that this is due at least in part to the high pressure at which ink is fed to the nozzle of a drop on demand printer which ejects the solid deposits with the initial droplets ejected through the nozzle orifice. Furthermore, the use of such elevated pressures, typically 1 to 3 bar, also projects the droplet at a greater velocity than is possible with an impulse jet print head. The projection distances which can be achieved with the valve of the invention are comparable to those which can

be achieved with a conventional continuous jet ink jet printer. However, the construction and operation of a drop on demand ink jet print head using the valve of the invention are simpler than for a continuous jet print head.

We have also found that the droplet formation and droplet trajectory of a drop on demand ink jet print head using the valve mechanism of the invention are enhanced as compared to a conventional drop on demand printer. We believe that this is at least in part due to the length to diameter ratio of the nozzle bore. A jewel nozzle as used in a conventional drop on demand ink jet printer has a length to diameter ratio of at least 8:1, typically about 10:1, and such ratios have been considered necessary to achieve directionality of the flight path of droplets ejected from the nozzle orifice. However, when such a nozzle is used at droplet generation frequencies of more than 1 kHz, we have found that for a given ink, printer operating pressure and droplet flight velocity, the printed dots formed are distorted. Surprisingly, we have found that by reducing the length to diameter ratio of the nozzle bore to less than 8:1, notably less than about 5:1, particularly to 1:1 to 2:1, these distortions can be reduced to an acceptable level without affecting the directionality of the flight path of the droplets ejected from the nozzle. Furthermore, by reducing the length of the nozzle bore, the pressure drop across the nozzle is reduced, allowing a faster exit velocity to be achieved at the nozzle orifice. Surprisingly this is achieved without causing spraying of the droplets, that is the break up of

the droplet at the nozzle orifice into a plurality of smaller droplets. This enables a higher frequency of droplet generation to be achieved at a given ink pressure for a given length of flight path.

However, we have also found that if the length to diameter ratio is reduced to below about 1.5:1, spraying of the droplets at the nozzle orifice begins to occur, notably when the ratio is reduced to below 1:1, even though the frequency of droplet formation is below than at which an impulse jet printer having an even smaller length to diameter ratio for the outlet nozzle operates without causing spraying of the ejected droplets.

We believe that the directionality of the flight path may also be due at least in part to achieving a smooth internal surface of the nozzle bore and thus reducing boundary friction and eddies within the fluid flowing through the bore. We also believe that the use of a nozzle orifice which is of substantially the same diameter as the nozzle bore upstream of the nozzle orifice is a major factor in reducing loss of directionality in the reduced length to diameter ratio bores in the valve of the invention. We believe that a further factor in improving the directionality of the droplet trajectory is achieved by a preferred form of construction of the nozzle.

In a conventional drop on demand print head, the nozzle orifice is provided by a jewel nozzle which is set into the distal end of a bore in the nozzle plate. We have found that there are minor errors in aligning the nozzle

accurately within its seat. As a result, the flight path of the droplets ejected from such a nozzle may be inaccurately directed. Whilst this effect can be compensated for with a single nozzle print head, this is more complex and difficult with a multi-nozzle print head. With a conventional 10:1 length to diameter bore, the collimating effect of the bore largely ensures that a given nozzle will perform with consistent flight path directionality, so that compensating for any inaccuracy in alignment of the nozzle can be achieved. However, where the length to diameter ratio of the nozzle bore is reduced, it would be expected that this would reduce the collimating effect and thus the consistency of the directionality of the droplet flight path from such a nozzle.

In a preferred embodiment of the invention, the valve of the invention is used with a nozzle plate having a plurality of nozzle bores which are formed substantially simultaneously in a single operation so that the nozzle plate has a unitary construction without the use of jewel nozzles. Such a simple unitary nozzle structure can readily be made using a wide range of techniques and overcomes the problems associated with misalignment of jewel nozzles in a multi-nozzle print head.

Accordingly, from a further aspect the present invention provides a multi-nozzle print head comprising a nozzle plate having a plurality of nozzle orifices, each at the distal end of a nozzle bore through the nozzle plate, characterised in that the nozzle bores are formed

substantially simultaneously and the nozzle plate and nozzle orifices are of a unitary construction.

It is surprising that the combination of the features of construction of the valve of the invention and a nozzle plate associated with the valve of the invention should be capable of producing uniformly sized and shaped droplets over a wide range of orifice diameters, for example from 20 to 400 micrometres, and at frequencies of droplet production in excess of 1.5 Khz and up to 8 Khz and for a wide range of ink compositions and viscosities.

The invention thus provides a compact and simple construction valve mechanism which is capable of producing uniformly sized droplets at its nozzle orifice at high frequencies of operation with low energy requirements and which achieves high resolution printed images, notably where the valve is used with a unitary construction nozzle plate to form a print head having an array of nozzles.

The valve of the invention can be used wherever it is desired to eject accurately sized droplets of a fluid at frequencies in excess of 1 Khz. Thus, the valve may be used to administer accurate doses of a reagent in a diagnostic test in the medical field, small amounts of a reagent in a chemical process or in analytical processes. However, the valve of the invention finds especial application in drop on demand ink jet printers where the fluid to be passed through the valve is an ink and the valve is used to print a visible or non-visible image on a substrate. For convenience, the invention will be

described hereinafter in terms of this application.

As indicated above the plunger is of unitary construction and is made from magnetically soft material having the specified properties. It is also preferred that the material have as high a saturation flux density as possible. Thus, the material may have a saturation flux density of 1.8 or higher. However, where the material has a saturation flux density of 2.0 or more, for example about 2.2, we have found that such materials usually contain high proportions of iron and are susceptible to corrosion be the inks normally used in an ink jet printer. Where such high iron content materials are used, it may be necessary to provide the plunger with a corrosion resistant or protective surface or coating. Thus, for example, the surface of the plunger may be provided with a polymeric coating. However, it is preferred to form a metallic layer on the plunger, for example of nickel or cadmium using any appropriate technique, for example electro- or vapour deposition.

Suitable materials for present use as the plunger material are available commercially and many are alloys of iron and nickel, typically containing 40 to 55% of nickel, preferably an alloy containing from 45 to 50% nickel and 55 to 50% of iron. If desired, other metals, for example cadmium, vanadium, chromium or aluminium, may also be present in minor amounts. Preferred materials for present use are those which have a saturation flux density in excess of 1.6 Tesla, for example 1.8 Tesla of more. The coercivity is less than 50, notably about 25, amperes per

metre. The relative magnetic permeability is preferably in excess of 50,000, for example 75,000 to 100,000 or more. Suitable materials for present use include those ranges of alloys sold under the Trade Names Permenorm 5000 and Vacofer SI.

The plunger may be formed wholly from such materials, for example by drawing or machining a cylindrical or other shaped plunger from the solid material using any appropriate technique. Alternatively, the plunger may be formed from a fritted, pressed or cast polymeric or ceramic carrier having particles of a suitable ferromagnetic material or mixture of materials dispersed therein. In a further alternative, the material from which the plunger is formed may be a laminate of different forms of ferromagnetic material to give a composite structure having the required overall properties. For convenience, the invention will be described hereinafter in terms of a unitary plunger formed from a solid body of a single Ni/Fe alloy.

The plunger is conveniently formed by machining, rolling or extruding the desired alloy to form a length of material having the desired size and shape. As indicated above, it is particularly preferred to form the plunger as a generally cylindrical member having a diameter of less than 2.5 mms and a length to diameter ratio of more than 3:1, preferably 5:1 to 10:1, since such a plunger can be used to provide a compact construction for the valve.

Where the plunger has a diameter greater than about 2.5

mms, part of the core of the plunger can be removed to form an internal bore within the plunger extending from the distal end of the plunger. This reduces the mass of the plunger. Surprisingly, this does not affect the magnetic properties of the plunger to a significant extent and the plunger behaves magnetically as if it were a solid member. For example, an axial bore can be formed as a blind ended drilling from the distal end in a solid rod of a suitable material. Preferably, the bore does not extend axially into that portion of the plunger housed within the coil when the plunger is fully retracted into the coil so that that portion of the plunger within the coil is solid. This maximises the magnetic force which acts upon the plunger during initial extension of the plunger from the coil when the coil is energised. Such a method for reducing the mass of the plunger is much simpler that the complex two component structure described in PCT Application No SE97/01007.

Accordingly, the present invention provides a solenoid valve, notably one of the invention, characterised in that the plunger has formed extending from the distal end thereof an internal bore or cavity, whereby the mass of the plunger is reduced, said bore or cavity extending axially within the plunger proximally no further than that point at which the plunger enters the bore within the coil when the plunger is fully retracted into the coil.

The material from which the plunger is made may undergo a change in its magnetic properties during machining or other working of the material during formation of the

plunger. It may be desired to subject the plunger after its has been formed to a heat treatment to caused the properties of the material to revert to the initial levels.

For simplicity, the invention will be described hereinafter in terms of a solid plunger.

The plunger will typically have a circular cross section and be a sliding fit within the cylindrical bore which extends axially within the coil so that it can be reciprocated smoothly within the coil. However, it is within the scope of the present invention for the plunger to have a polygonal or other non-circular cross section and/or for the bore in the coil to be non-circular, so as to provide axial fluid flow passages between the plunger and the coil. This will allow fluid to be displaced from the proximal end of the coil bore as the plunger is retracted into the coil and thus reduce fluid damping of the movement of the plunger. Alternatively, or in addition, these passages may be used to feed fluid from an inlet at the proximal end of the valve assembly to the valve head chamber at the distal end of the coil. For example, the plunger can be formed with two or more axial flats which co-operate with the walls of a cylindrical coil bore to allow fluid to flow past the plunger. Such fluid flow may also serve to cool the plunger and coil during operation of the valve.

As stated above, the nozzle bore between the valve head chamber and the nozzle orifice differs from that used in

either a conventional drop on demand print head or an impulse jet print head in that the length to diameter ratio of the bore is typically less than 5:1 as compared to the 10:1 and greater ratio used in a conventional drop on demand print head and is greater than about 1.5:1 as compared to the less than 0.5:1 ratio used in an impulse jet head. We prefer that the length to diameter ratio be from 1:1 to 5:1, notably 1.5:1 to 3:1.

The nozzle bore diameter can be selected over a wide range. Thus, we have found that the valve of the invention can have a nozzle bore diameter of up to 400 micrometres where it is desired to apply a fluid having a high viscosity, for example up to 400 Cps at 25°C to coat fibres during the printing of textiles and fabrics having long fibres, typically longer than 1 mms. The valve of the invention permits the operator to select short bore lengths at large bore diameters for such high viscosity fluids without sacrificing accuracy of droplet placement. With a conventional 10:1 ratio nozzle for a drop on demand printer, the pressure required to eject such a high viscosity ink is excessive unless very large diameter bores are used. Alternatively, the bore diameter may be as small as 20 micrometres when printing high definition images using inks having a viscosity of less than 20 Cps, typically 1 to 10, notably between 2 and 5, Cps. The optimum combination of bore length to diameter ratio within the range 1:1 to 8:1 and bore diameters in the range 20 to 400 micrometres at a given ink pressure can readily be determined by simple trial and error tests.

Surprisingly, we have found that the valve of the invention can be used successfully to apply inks to long pile fibres in fabrics or textiles, for example to carpet fibres or long pile woven fabrics, where the fibre or pile has a length of 1 mm or more, notably those with pile lengths of 3mms or more, without the need to use very high viscosity inks as has hitherto been considered necessary to ensure even coating of the fibres with the dye of the ink. We have found that the valve of the invention can be operated with inks have viscosities of from 50 to 150 Cps and with nozzle orifices of from 80 to 250 micrometres in applying ink to such long pile fabrics.

Accordingly, the present invention provides a process for applying an ink or dyestuff having a viscosity of from 50 to 150 Cps at 25°C to a fabric or textile having a pile length of 1 mms or more using a drop on demand print head incorporating a valve of the invention having a nozzle orifice of from 80 to 250 micrometres and operated at a frequency of 1 kHz or more.

We have found that the amount of fluid remaining in the bore to the nozzle orifice of the valve of the invention after the ejection of a droplet from the nozzle orifice is usually smaller than can be achieved with a conventional drop on demand print head. This is particularly the case where the length to diameter ratio of the nozzle bore has the effect of achieving a nozzle bore volume which is approximately equivalent to the volume of ink which is to be ejected at each actuation of the valve, notably where the length to diameter ratio is about 2:1. As a result,

the damping effect of the inertia of this fluid on the movement of the plunger of the valve of the invention is reduced, further assisting rapid movement of the plunger under the influence of the coil thus assisting high frequency operation of the valve.

As stated above, the nozzle orifice diameter is substantially the same as the diameter of the bore upstream of the orifice. We have found that this is an important factor in reducing turbulence in the flow of fluid through the nozzle orifice and rapid expansion of the droplet leading to break up of the droplet as it exits the nozzle orifice. Whilst such a construction can be achieved by inserting a suitably dimensioned jewel nozzle into the distal end of the bore between the valve head chamber and the nozzle orifice, we have found that this may result in inconsistent flight paths for the droplets ejected from a multi-nozzle nozzle plate. Furthermore, it is often impossible to obtain jewel nozzles having the desired length to diameter ratio for bore diameters of less than about 40 micrometres. We therefore prefer to form the nozzle orifice as the distal outlet of the nozzle bore and to dispense with the use of a separate jewel or other nozzle member to provide the nozzle orifice. Thus, in a preferred embodiment, the nozzle orifice and bore are formed as a unitary structure, for example concurrently as a bore is cut or otherwise formed in a plate upon which the valve mechanism is to be mounted. For example, the bore/nozzle orifice is formed in a nozzle plate by a laser, microelectro-machining or etching, needle punching or other techniques. The nozzle plate can be from 50 to

400 micrometres thick so as to achieve the desired length to the bore. At such thickness, the nozzle plate takes the form of a metal or other foil which is mounted in a suitable support member to provide a rigid and mechanically strong nozzle plate assembly. We have found that by forming the nozzle bores simultaneously in a multi-nozzle nozzle plate, problems due to misalignment of the bores with one another are minimised.

We have also found that by selection of the bore forming technique, the walls of the bore are sufficiently smooth to reduce flow separation and the formation of eddies at the interface between the bore walls and the fluid flowing through the bore. Furthermore, such techniques may also be used to form other features on the nozzle plate which enhance the operation of the valve. For example, electro-machining or etching of a metal foil can be used to form the bores/nozzle orifices in the plate and also to form a raised lip or ridge around the inlet to the bore leading to the nozzle orifice. This provides a localised pressure point between the distal end face of the plunger and the nozzle plate to assist the formation of a fluid tight seal when the plunger is in the valve closed position. Alternatively, where a needle is used to form the bore in a metal foil, this will cause the foil to deform and form a belled entry to the bore which will assist smooth flow of fluid into the bore from the valve head chamber. The penetration of the needle through the foil may also polish the surface of the foil, and hence the internal wall of the bore which is formed, as the surface of the needle slides over the material of the foil. Similarly, the use

of a laser to form the bore in a metal, ceramic or plastic foil may also form a polished surface to the walls of the bore, notably where the laser beam is pulsed for very short periods, typically less than 1 nanosecond, to reduce the formation of deposits around the lip of the bore of material which has been ablated from the plate in forming the nozzle bore.

Accordingly, from another aspect the present invention provides a solenoid valve, notably a valve of the invention, characterised in that the nozzle orifice and the bore from the valve head chamber to the nozzle orifice are formed as a unitary construction. Preferably, the outlet nozzle and the bore are formed as a bore within a foil nozzle plate having a thickness of up to 400 micrometres, the bore having a length to diameter ratio of less than 8:1, preferably 1:1 to 5:1. Preferably, the bore has a polished internal surface so as to reduce flow separation or eddies in fluid as it flows through the bore.

The valve mechanism of the invention has a coil through which an electric current is passed to generate the magnetic field which acts upon the plunger. In conventional designs of solenoid valve, such a coil is wound upon a bobbin, for example of a suitable insulating plastic. The bobbin is then located upon a tubular member which forms the support for the bobbin and provides the walls of the axial bore within which the plunger reciprocates. We have found that it is desirable to minimise the radial air gap between the conductor of the

coil and the plunger so as to optimise the magnetic coupling between the coil and the plunger. This can be achieved by winding the conductor of the coil directly upon the tubular member within which the plunger reciprocates, with a thin insulating interface between the wire of the coil and the tubular member where a metal tube is used. Alternatively, the coil can be formed by winding a bare wire coil upon an insulating tubular member and then retaining the coil in position by applying a retaining coat of resin or other binder upon the wound coil. Alternatively, the coil can be wound upon a mandrel or other former, removed from the former and then potted in a suitable resin which forms the wall of the tubular member within which the plunger reciprocates. In a particularly preferred embodiment, the tubular member is formed from a ceramic material, for example as a ceramic frit tube or electro-etched silicon tube. The coil can be formed by depositing a conductor track, for example by vapour phase or electrical deposition of a copper, gold or silver conductor or track, upon the surface of the tube or into grooves etched, machined, laser cut or otherwise formed in the external surface of the tube. Alternatively, the coil may be formed as a copper, silver, gold or other conductive track upon a flexible circuit board which is then rolled upon a mandrel to form a cylindrical tubular member incorporating the coil.

In all such designs of the coils for present use, the radial distance between the conductor of the coil, including the sliding clearance between the plunger and the wall of the bore in the tubular support for the coil

conductor and the thickness of that support, has been reduced, typically to a radial dimension of less than 2mm. The radial air gap between the plunger and the wall of the tubular member within which it reciprocates is reduced to less than 200, preferably less than 100, for example 50 to 75, micrometres. This is compared to the 1 mm or greater air gap in a conventional solenoid coil. Such a reduction in the radial dimensions and the air gap results in greater efficiency in coupling the plunger magnetically to the coil, resulting in lower power consumption and greater speed of response of the plunger to changes in the current flowing in the coil. Such constructions also result in a unitary construction for the coil and the tubular member within which the plunger reciprocates, thus simplifying construction and assembly of the valve.

The invention thus also provides a solenoid valve, notably a valve of the invention, characterised in that the conductor of the coil of the solenoid is deposited, wound or otherwise formed upon or within the wall of a tubular support member which provides the interface between the conductor of the coil and the plunger which is journalled for sliding engagement within the support member. Preferably, the conductor of the coil is carried directly by the support member which is in direct sliding engagement with the plunger.

As indicated above, the solenoid valve also comprises a valve head chamber which houses the distal end of the plunger and is provided with the outlet nozzle bore to the nozzle orifice. Such a chamber typically is of generally

circular cross section and has a transverse end closure wall having the outlet and the nozzle bore to the nozzle orifice formed therein. If desired, the tubular support member for the coil can be longitudinally extended to provide the radial walls of the valve head chamber. In one embodiment of such a construction, the tubular member is formed as a cylindrical tube having one end closed to form the transverse terminal wall of the valve head chamber, the wall being pierced by a bore whose free end provides the nozzle orifice. Such an assembly can readily be formed by electroforming or laser etching of a silicon or ceramic member to high accuracy using automated techniques.

The valve mechanism is preferably used in co-operation with a plurality of closely adjacent valve mechanisms, each serving one or more discrete nozzle orifices to form an array type print head capable of applying a plurality of dots of fluid to a substrate to create a two dimensional image on a substrate. Such an array can be formed by mounting the outlet end of the valves upon a nozzle plate with a bore through the plate providing the nozzle bore from the valve head chamber of the valve to the nozzle orifice. Preferably, the valves are located in staggered rows to achieve as close a spacing for the nozzle orifices in the nozzle plate. If desired, the nozzle bores from each valve head chamber can be at an angle to permit the valve bodies to be offset from the centre line of the nozzle plate to enable the nozzle orifices to be more closely spaced. In a particularly preferred embodiment, the nozzle plate is provided with a

series of upstanding tubes, each in register with one of the bores through the plate. The tubes serve as the support for the coil of the valve and the plunger reciprocates within that tube. The distal end portions of the tubes adjacent the nozzle plate, or the proximal portion of the bore in the nozzle plate, serves as the valve head chamber of the valve mechanism. Such arrays can be formed from ceramic or silicon materials using automated techniques and the nozzle orifice can be provided either by a jewel nozzle set into the distal end of the bore through the nozzle plate or by forming a suitable nozzle orifice in the end of a blind end bore in the nozzle plate as described above. Such assemblies can be formed on a very small scale enabling miniaturisation of the valve structure to be achieved. It is preferred to provide the nozzle plate as a metal, ceramic or other foil having the bores formed therethrough as described above and to mount that plate so that the bores therein are in register with the distal ends of the plungers of the valves. In this case, the valve head chambers can be individually formed in the surface of the foil or in an intermediate plate located between the valve coil support members and the nozzle plate. However, we have found that the flow of ink or other fluid to the individual bores and nozzle orifices is enhanced if the intermediate plate is formed with a continuous chamber which provides a combined valve head chamber for all the valves in the print head assembly. In such a construction, the seal between the distal end face of each plunger and the registering bore in the nozzle plate provides adequate isolation of flow through each of the nozzle bores and orifices. The

opposing faces of the nozzle plate and the distal end of the plungers are preferably provided with sealing means to assist the formation of a fluid tight seal when each plunger is in the closed position. For example, the end face of the plunger can be provided with a natural or synthetic rubber or polymer face which deforms to provide a seal against the opposed face of the nozzle plate. The face of the nozzle plate can be provided with one or more annular raised ribs or the like which provide localised raised pressure areas to assist formation of the fluid tight seal. Such raised areas can readily be formed on the face of the nozzle plate during the electro-forming or etching of the nozzle plate.

If desired the raised areas on the nozzle plate can be formed from a flexible material to cushion the impact of the end face of the plunger against the nozzle plate. Such deformation may also assist formation of the fluid tight seal where the end face of the plunger does not carry a rubber or similar pad. If desired, the pad carried by the end face of the plunger can be formed from a material which undergoes cold creep or deformation under the load of the bias spring urging the plunger into the valve closed position. Such creep may form a nipple or other projection which extends into the proximal portion of the nozzle bore in the nozzle plate. Upon reciprocation of the plunger, this projection repeatedly wipes at least the initial part of the proximal portion of the nozzle bore and displaces solid deposits which may have deposited upon the wall of the bore and this may assist in reducing initial drop deformation after rest

periods of the valve. To assist the operation of this projection, the mouth to the inlet to the bore through the nozzle plate may be belled, as may occur when a needle is used to form the bore in the nozzle plate.

The invention also provides a print head for use in a drop on demand print head in which the solenoid valve mechanisms are each mounted in register with one of a plurality of bores through a nozzle plate, characterised in that the nozzle plate is a foil member having the bores therethrough and each bore is provided with a valve head chamber adapted to receive the distal end of the plunger of the valve mechanism associated therewith. Preferably, the valve head chambers are provided as a single chamber extending over a plurality of the bores in the nozzle plate to provide a common flow path to the bores and their associated plungers. Preferably, the nozzle plate is provided with two or more rows of nozzle bores, which may be staggered to assist close packing of the valve mechanisms associated with each nozzle bore.

Where the valves of the invention are mounted in close proximity with one another to form a print head containing a plurality of nozzle orifices, it is preferred to provide each valve mechanism with a metal housing to the coil thereof which acts not only as a return path for the magnetic field generated by the coil within it, but also acts as a magnetic screen so as to reduce cross talk between the magnetic fields generated by one coil and the coil of an adjacent valve mechanism. Typically, such a metal housing is made from μ-metal, aluminium or stainless

steel and also acts as a rigid housing for the components of the valve mechanism. Thus, the housing can be of a generally cylindrical form and can be crimped radially inwardly at each end thereof to retain the coil assembly. The distal end of the metal housing can be crimped or otherwise secured to the nozzle plate where the nozzle plate carries upstanding tubular members as described above.

As stated above, the valve mechanism preferably also comprises a spring member to provide the bias to return the plunger to its rest position when a current is not applied to the coil. Typically, the spring is a compression spring and acts to bias the plunger against the inlet at the proximal end of the bore to the nozzle orifice, so that the rest position of the plunger is in the valve closed position. When a current is applied to the coil, this opposes the bias of the spring and moves the distal end of the plunger away from the bore inlet to open a flow path from the valve head chamber to the nozzle orifice. However, it will be appreciated that the rest position may be the valve open position and the operative position is the valve closed position. For convenience, the invention will be described hereinafter in terms of the rest position being the valve closed position.

The spring member is pre-tensioned, for example from 50 to 80% of the travel of the compression of the spring is taken up by the pre-tensioning, since we have found that such pre-tensioning enables the spring to apply a consistent bias force against the movement of the plunger

over the remainder of the compression of the spring during movement of the plunger. We have found that the use of a conical spring is of especial benefit since such springs can readily be fitted within the dimensions of the valve head chamber and will tend to be self centring during the assembly of the valve mechanism, whereas conventional cylindrical coil springs do not. Furthermore, the use of a conical spring reduces the mass and hence inertia of the spring, further aiding rapid response of the spring to movement of the plunger. It is particularly preferred to use a conical coil spring which is pre-tensioned to the last two turns of the spring, since we have found that such a spring responds rapidly to the movement of the plunger and the pre-tensioning enables the spring to exert a significant bias force over a small additional compression of the spring.

Fluid can be fed to the valve head chamber by any suitable means, for example by one or more radial inlet ports in the side wall of the chamber. Alternatively, as described above, the plunger and/or the internal wall of the tubular support for the coil can be formed with axial flats or passages so that fluid flows axially past part or all of the plunger within the coil so that the fluid lubricates the movement of the plunger within the coil and can also act to cool the coil at high current loadings and/or high frequencies of operation of the valve. Where the valve mechanism is used as party of an array print head having a plurality of nozzles, it will usually be preferred to feed at least part of the ink or other fluid by means of a manifold plate in which inter-connecting valve head

chambers are formed so that ink may flow freely along an elongated chamber to aid uniform flow to each nozzle bore in the associated nozzle plate as described above.

The valve of the invention is capable of being operated at high frequencies, typically in excess of 1.5 kHz, for example at from 2 to 5 kHz, and as described above finds especial application as the solenoid valve in a drop on demand ink jet printer head. In such an application, the valve is desirably as small and compact as possible so as to reduce the overall size of the print head and the inertia of the components of the valve mechanism, for example in the application of inks or dyes to long pile fabrics or textiles as described above. However, it will be appreciated that the valve mechanism of the invention may be used wherever a small, high speed valve is required, for example in the dosing of measured amounts of a reagent in a chemical or biological analysis or other process, notably in the assessment of medicaments or in diagnostic testing or analysis. The valve of the invention also finds use in applying a predetermined quantity of a reagent in the verification of the authenticity of a sample.

In a conventional drop on demand printer, the operation of each solenoid valve is triggered in response to a signal from a computer or microprocessor, which determines which valve is opened and when so as to eject a droplet from a specified nozzle at the correct time to print the desired image on a substrate. The computer may also be used to control the open time of each valve so as to regulate the

size of the dot printed on the substrate. We have found that the ability to control the operation of the valve using software has a number of other significant benefits which enable the valve of the invention to deliver high quality printed images at much higher frequencies that has hitherto been considered possible for a drop on demand print head.

Thus, it is particularly preferred to use software to calibrate the valve during its manufacture so that under specific conditions it delivers a consistent droplet of ink through the nozzle orifice. With conventional designs of solenoid valve, it is necessary to compensate for minor variations in dimensions and materials of the manufactured valve by physically adjusting the axial travel of the plunger so as to vary the size of the flow path created when the plunger is withdrawn from sealing engagement with the transverse end wall of the valve head chamber or the tube leading to the nozzle orifice. This will affect the size of the dot ejected from the nozzle orifice and the objective of the calibration process is to achieve a uniform droplet size from all the nozzle orifices in a print head under the same printing conditions. The conventional design of solenoid valve incorporates a stop within the bore of the tubular support for the coil, which stop provides a physical limit to the axial movement during retraction of the plunger. In such a conventional valve design, the axial air gap between the proximal end of the plunger and the stop is adjusted, for example by making the stop a stiff push fit or a screw fit within the tubular support, so that it can be moved axially within

the bore of the tubular member to achieve the desired air gap. Such adjustment of the air gap is tedious and time consuming and is prone to operator error. We have found that software can be used to set a specific point in the retraction of the plunger at which the plunger movement halts and thus the time and extent to which the valve is open. This point can readily be adjusted by simple modification of a parameter of the software, for example by keyboard input of a new value for that parameter. Such adjustment can be achieved accurately and the calibration carried out for a number of sets of printing conditions so that the current pulse amplitude and duration required to achieve given droplet sizes can be determined and stored, for example in as a machine readable code on a magnetic disc, look up table in a memory chip or other storage medium, for future use with that valve. The calibration can be achieved simply and at smaller increments of droplet size than is possible with screw adjustment of the stop in conventional design of solenoid valve.

In carrying out the calibration, droplets are printed onto a substrate whilst operating the valve under standard conditions and at a given electric current pulse amplitude and duration applied to the coil. The size and form of the droplet formed at the nozzle orifice and/or the printed dot is examined by any suitable means and the amplitude and/or duration of the electric pulse raised or lowered to achieve the desired dot size. Such a process can be carried out manually. However, it is preferred to carry out this process automatically by inspecting the droplet at the nozzle orifice and/or the printed dot using

a CCD camera or other inspection means and comparing the form of the droplet or printed dot with parameters for the required droplet or dot. Such comparison and subsequent adjustment of the current pulse can be carried out using a suitably programmed computer. It is especially preferred to monitor the diameter and circularity of the printed dot and the presence of satellite small dots adjacent the desired dot using a CCD array or camera and comparing the dot characteristics with those held in a look up table which identifies the correction which needs to be applied to the current pulse applied to the coil to achieve the desired printed dot characteristics. The optimum variation in the operation of the valve mechanism, for example to increase or reduce the open time of the valve, can be determined by trial and error tests and the optimum value of the variation then stored in a look up table or other storage medium to provide one of the parameters against which the printed dot and the operation of the print head is assessed.

The use of a CD camera or array and computer to inspect the droplet at the nozzle orifice and/or the printed dot and to modify the current applied to the coil of the valve also has applications during the operation of the valve during printing of images. Thus, the computer can be programmed to decelerate the movement of the plunger at either or both extremes of its travel. We have found that this reduces splatter of the ink from the nozzle orifice due to sharp impact of the plunger against the seal members at the entry of the bore between the valve head chamber to the nozzle orifice. As indicated above, this

may also reduce wear on the sealing components of the nozzle plate and the end face of the plunger. The use of software can be used to compensate for fluctuations in the viscosity of the ink due to temperature variations or other reasons; variations in voltage applied to the different coils in an array of print heads which are operated simultaneously; and to compensate for other changes in operating conditions, for example the use of a different ink, which require changes in the form and size of the electrical pulse applied to the coil of the valve. The use of software can also be used to hold a valve in the open position to print a continuous line of ink in place of the series of overlapping dots achieved with present print head operating techniques. As stated above, this enables a lower current to be passed through the coil during the hold open status after the initial larger current has be applied to open the valve. If desired, the open time of the valve can be increased to compensate for the initial droplets ejected from the nozzle orifice following a rest period of the valve.

In all cases the operation of the valve is modified by the computer in response to a signal from the CCD camera or other mechanism used to inspect and monitor the droplet at the nozzle orifice and/or the printed dot and to compare the observed droplet or dot to parameters held in a memory of the computer or another storage medium so as to determine what modification, if any, is required to the current applied to the coil so as to achieve the desired dot. The invention thus provides a print head of the invention operated under the control of a computer in

combination with a mechanism for observing the droplet formed at the nozzle orifice or the printed dot of ink or other fluid applied to the substrate, the computer being programmed to detect differences between the observed droplet and/or dot and the desired droplet and/or dot and to apply a correction to the current applied to the coil so as to maintain the desired observed droplet and/or dot parameters. This aspect of the invention may also be applied to conventional solenoid valve mechanisms to provide on-line optimisation of print quality. The invention also includes the provision of an audible and/or visual warning or alarm which is actuated when the quality of the printed dot departs beyond a predetermined value away from the desired dot form. If desired, that alarm or warning may also act to disable the operation of the printer.

Such a combination enables the printed droplet and/or dot quality (for convenience hereinafter referred to solely as the dot quality) to be monitored and corrected on-line during operation of the printer. Hitherto, the print quality was observed objectively by the operator of the printer and a correction to the operation of the printer applied manually. The ability to use the software on-line to achieve monitoring and correction of print quality is a major benefit to the operator and can achieve virtually instantaneous correction of fluctuations in print quality.

The monitoring and correction may be achieved using conventional software and hardware techniques and designs. The dot quality can be monitored continuously and a

correction applied in response to the average of three or more successive dots. Alternatively, the printed dot quality can be monitored at intervals, for example every second or at intervals of every twenty operations of the valve, and any correction applied once the printed dot deviates by more than say 5% in any one or more of the parameters used to assess the quality of the printed dot.

Typically, the monitoring of the printed dot quality will be used to apply a signal to vary the open time of the valve. The software may also be used to operate the valves forming a printed raster alternatively rather than in strict sequence. Thus, the software can operate valves 1, 3, 5 and 7 simultaneously, and then valves 2, 4, 6 and 8 to achieve overlap of the printed dots by suitable time delay and thus achieve better definition in the printed image.

It will be appreciated that the signal indicating that some variation of the operation of the valve is required may be provided from an external source rather than from the on-line scanning of the printed dot. Thus, a sensor may monitor the operating temperature of the printer and/or of the ink fed to the valve, since this will affect the viscosity and hence the jet-ability of the ink. Such sensors may monitor the voltage applied to the valve mechanism, for example the voltage drop which occurs when a plurality of valves are operated simultaneously from a single power source, the time for which a specific valve has rested between printing operations, the frequency of operation of a valve and so on. These sensors may then

address a series of look up tables which then set the variation of the open time required to reduce defects in quality of the printed dot if the parameter being monitored varies from a predetermined optimum value.

It is preferred that the quality of the printed dot from each nozzle be monitored individually. However, if desired the printed dot quality from groups of nozzles may be monitored collectively.

In the conventional computed control of the operation of a valve in a drop on demand printer, simple single bit signals are used to open and shut the valve since all that has been required hitherto is that the computer instruct the valve to open and shut so as to print a dot of the required size. However, the ability to vary the operation of each valve individually during the operation of the printer in response to many inter-related factors requires the transmission of more complex signals than simple open and shut instructions. We have found that it is desirable to transmit signals in byte format so that the amount of information transmitted can accommodate the permutations of operating parameters desired. Thus, for example, the use of byte form signal transmission offers 256 possible graduations of open time of the valve. This enables the amount of ink deposited in each printed dot to be varied over a very wide range by providing a look up table with 256 individual addresses therein from which the computer controlling the operation of the printer can instruct the open time of the valve to be selected. This enables a true grey scale image to be printed using a drop on demand

print head, which has not hitherto been considered practical. The use of byte signal transmission enables a wide selection of values for variation of a given operating parameter to be transmitted and responded to rapidly and accurately, further enhancing the speed and accuracy of operation of the print head. This, coupled with the high frequency printing of consistent quality dots over a wide range of sizes and speeds, enables the present invention to extend the use of drop on demand printers into fields of use for which they have hitherto not been considered possible whilst retaining the flexibility of printed dot size which cannot readily be achieved with other forms of printer. Thus, it is possible to mount two or more print heads generally parallel to one another and to delay the operation of the valves in the various print heads so that droplets are ejected from subsequent print heads in closely adjacent or overlapping positions. This can be used to provide continuous printing where the ejected droplets overlap one another, or can be used to enhance the definition of the printer image by depositing successive droplets closely adjacent to one another, notably where the droplets are small. Where the information controlling the operation and delay of the various valves is in 256 bit format, it is possible to achieve a closer spacing of the droplets than is possible using previous operating techniques. This enables true grey scale printing and very fine definition printing.

Accordingly, the present invention also provides a method of operating a drop on demand printer under the control of

a computer, characterised in that the operating control signals from the computer are of a byte form and the look up tables from which the computer selects the variation in the operation of the printer to be effected contain up to 256 possible selections.

DESCRIPTION OF THE DRAWINGS:

A preferred embodiment of the invention and its operation under on-line software control will now be described by way of illustration only and with respect to the accompanying drawings, in which Figure 1 is a diagrammatic axial cross section through a valve of the invention; Figure 2 is an axial cross section through a drop on demand ink jet print head incorporating an array of the valves of Figure 1; Figure 3 is plan view of the nozzle plate of the print head of Figure 2; Figure 4 is a diagrammatic block diagram of an array of Figure 2 in combination with a CCD camera for monitoring the quality of the printed dots and a computer for establishing what variation to the frequency, form, shape and amplitude of the electrical pulse applied to the coil of the valve of Figure 1 is required to compensate for any deviation in the quality of the observed printed dot; and Figures 5 to 8 illustrate variations in the construction of the valve of Figure 1.

DESCRIPTION OF THE PREFERRED EMBODIMENT:

The valve of Figure 1 comprises a plunger 1 which is journalled as a close, free sliding fit for axial

reciprocation in a stainless steel tube 2. Tube 2 has a thin insulating coating or sleeve (not shown) formed upon its outer face and supports a coil 3 wound upon it. Coil 3 is supplied with an electric current from a source (not shown) under the control of a computer 20, shown in Figure 4. A stop 4 is mounted at the proximal end of tube 2 to limit the axial retraction of plunger 1 within tube 2. The coil 3 is encased in a metal cylindrical housing 5.

The above assembly is mounted in a support housing 10 which extends axially beyond the distal end of the coil and has a transverse end wall 11 which carries a jewel nozzle 12. In the embodiment shown in Figure 1, housing 10 has an axially extending internal annular wall 13 which forms the radial wall of the valve head chamber 14 into which the distal end of the plunger extends. The distal end of the plunger 1 carries a terminal rubber or other sealing pad 15 which seats against the proximal end face of jewel 12 in sealing engagement. A pre-tensioned conical spring 16 biases plunger 1 into sealing engagement with the face of the jewel as shown in Figure 1, the rest or valve closed position.

Plunger 1 is made from a ferromagnetic alloy having a saturation flux density of 1.6 Tesla, a coercivity of 0.2 a/m and a relative magnetic permeability of 100,000. In order to reduce the mass of the plunger 1, it may have a blind internal bore extending from the distal end thereof. However, this bore should not extend beyond line A-A shown in Figure 1 when the plunger is in its rest position. It is also desirable that the plunger have a diameter of less

than 3 mms, typically about 1 mm, and a length to diameter ratio of about 5:1. The nozzle bore in the jewel nozzle has a diameter of 60 micrometres and an l:d ratio of from 2:1 to 3:1 and the orifice at the distal end of the nozzle bore has a diameter of 60 micrometres. Ink is fed under a pressure of 1 bar to an ink gallery 17 encompassing wall 13 and enters the valve head chamber via radial ports 18. When the plunger is in its rest position as shown in Figure 1, the pad 15 is in sealing engagement with the face of the jewel nozzle 12 and thus prevents flow of ink through the nozzle orifice. In order to enhance the seal between the pad 15 and the jewel 12, we prefer to provide the proximal face of the jewel with one or more raised annular sealing ribs (not shown).

Such a valve can be operated at frequencies of from under 1 kHz to over 8 kHz to produce consistently sized droplets in the size range 60 to 150 micrometres by controlling the length for which the current flows in the coil 3 and the frequency at which such current pulses are applied to the coil.

As indicated above, the valve is preferably used in an array with other valves to form a print head which extends transversely to the line of travel of a substrate upon which an image is to be printed. Such an array is shown in Figures 2 and 3. In this case the terminal portion 11 of the housing 10 is provided by a trough-shaped nozzle plate 30 carrying the nozzles 12 and serving as a manifold to form the ink flow gallery 17 feeding ink from ink inlet spigots 31 at each end of the nozzle plate via the inlet

ports 18 to the individual valve head chambers 14 of the valves in the array. In a further alternative, the individual valve head chambers 14 are omitted so that ink from the gallery 17 flows directly into a nozzle bore when a plunger is retracted. The array is provided with a connector 32 by which individual electric current supplies can be fed to the coils 3 in each of the valves. In such an array, the housing 4 serves to reduce electrical and magnetic cross talk between adjacent valves in the array.

Such valves and arrays can be made by machining appropriate metal components. However, one alternative form of construction is to form the tube 2 as a ceramic or silicon member 40 as shown in Figure 5. The coil 41 can be formed in grooves 42 cut in the external surface of the tube 40 so that the air gap between the coil and the plunger 43 journalled within the tube is reduced. The coil 41 can be a wire coil wound into the grooves 42; or can be a conductive track which is deposited by any suitable means in the grooves 42. If desired, the assembly can then be coated with a polymer to retain and protect the coil within the grooves. In place of a rigid ceramic or silicon support tube, the tube 40 can be provided by a sheet of a flexible support medium, for example a suitable fibre filled polymer or the like, upon which a copper or other conductive track has been formed. The support medium is then rolled into a cylinder to form a cylindrical support carrying the coil upon its inner or outer face. In such designs, the tube 40 can extend axially to form the radial walls 44 of the valve head chamber and the distal open end of the tube closed with a

jewel nozzle 45. The whole assembly can then by encased in a stainless steel or other tube 46 which acts to support the assembly and provide the magnetic return path as screening for the coil. The ends of the tube 46 can be inwardly crimped to secure the tube 40, the coil 42 and the jewel 45 in position.

In place of the above forms of construction, an assembly of valves can be formed as shown in Figure 6 by forming a nozzle plate 50 from a silicon or ceramic frit or other material. This plate is provided with jewel nozzles 51 at the desired spacings along the plate 50. Plate 50 is provided with upstanding tubular members 52 which form the tubes 40 of the valve design of Figure 5. The coils 53 are wound or otherwise formed upon the upstanding tubular members 52 and the array is completed as in Figure 5. The valve head chamber 54 is formed by the terminal distal portions of the tubular members and radial ink inlet ports may be provided to enable ink to flow into the valve head chamber. A plunger 55 is journalled in tubular members 52 for axial reciprocation under the influence of coil 53. In place of the jewel nozzle forming the closed distal end to the valve head chamber, the plate 50 can be provided as a continuously extending plate so as to form closed ends to the upstanding tubular members 52. These closed ends can then be pierced, for example by a laser, to form the bores therethrough and the nozzle orifices.

In place of the radial ink inlet ports to the valve head chamber 14 or 54, ink can flow axially past the plunger 1 or 55 from an ink inlet to the axially extending space

between the tubular members 2 or 52 and the plungers 1 or 51. To form the axial passages past the plunger, the bore in tubular member 2 or 52 can have an oval or polygonal cross section and plunger 1 or 55 has a circular cross section. However, it is preferred to form plunger 1 or 55 with axial flats to it which provide axial passages between the plunger and the circular cross section bore of the tubular member as shown in Figure 7.

In a particularly preferred form of construction of the print head is shown in Figure 8. The nozzle plate 100 is formed with a plurality of bores 101 therethrough having a length of 120 micrometres and a diameter of 75 micrometres. The plate is made from stainless steel and the bores are formed either by needle punches or by laser drilling each hole. Alternatively, the bores 101 can be formed by micro electromachining the plate, which technique can also be used to form the raised annular ridge 102 around the inlet to each of the bores 101. This foil nozzle plate is clamped between two stainless steel support plates 103 and 104. Plate 104 is formed with a single manifold chamber 105 which extends over all the bores 101 formed in plate 100. Alternatively, the chamber 105 can be formed in plate 100.

A valve assembly 110 contained in a support housing 111 is secured to plates 100, 103 and 104 with each of the plungers in a valve mechanism within the assembly in register with a bore 101. The valve mechanisms comprise a coil wound upon a support tube 112 within which a plunger 113 is a loose sliding fit. Each coil is surrounded by a

stainless steel housing 114 which is crimped to an apertured support plate 115 clamped between housing 111 and plate 104 to locate and secure each valve mechanism with the plunger projecting through the aperture in register with a bore 101 in the nozzle plate 100. Each plunger 114 is made from a 45/55 Ni/Fe alloy sold under the trade mark Permenorm 5000 and is 1 mm in diameter and 7.5 mms long. The electrical contacts for the coils are fed from a multi-contact plug and socket from a computer controlled power source, not shown. The valve head chamber for each valve mechanism 110 is provided by the single manifold chamber 105 which is fed with ink from each end of plate 104.

As indicated above, the operation of the valve is controlled by a computer 20 in response to a CCD camera or array 21 or other sensors 22 detecting the quality of the printed dots and/or other factors such as temperature, voltage, frequency of operation of the valve which also affect the printed dot quality. Thus, the computer 20 determines which valve to open in the array of Figure 2 and for how long so as to print a drop of the desired size at the desired position on the substrate 23 passing the print head 24. At slow frequencies of operation, for example below I kHz, this will usually result in a good quality dot being printed on the substrate. However, as the frequency increases, say to 2 kHz or more, the quality of the printed dot may suffer, for example due to the sudden closure of the valve causing the formation of satellite dots. The computer can respond to this by detecting from the CCD array that such satellite dots are

being formed and causing the shape of the pulse of electric current applied to the coil to change so that the movement of the plunger at each extreme of its travel is reduced so as to reduce the sudden-ness of the closure of the valve by causing the plunger to soft land against the face of the jewel nozzle or end wall of the valve head chamber. Alternatively, the computer can respond to the instruction to print at high frequencies by reducing the open time of the valve by reference to a look up table 25 which carries a list of reductions in open time for a range of operating frequencies. Similarly, the software controlling the operation of the print head can detect when a valve has been idle for any length of time and provide, through another look up table, a signal to increase the open time of the vale for the initial dots printed by that valve to compensate for any drying out of the ink within the valve and/or at the nozzle orifice. In such cases, it is preferred that the information between the computer and the look up table be exchanged as bytes sized signals so that up to 256 possible permutations of open time and operating frequency can be accommodated in a single signal.

By way of comparison, when the plunger of the valve mechanism shown in Figure 1 is made from a conventional Carpenter 430 alloy having a saturation flux density of about 1.2 Tesla, a coercivity of about 95 A/m and a relative magnetic permeability of about 3,000, the valve cannot by reciprocated at frequencies greater than about 800 Hz. At current pulse frequencies for driving the coil of the valve above this, the plunger remains static within

the coil and merely vibrates without significant axial movement. We believe that this is due to the failure of the material of the plunger to be able to respond rapidly enough to the pulses of current and that the plunger remains at substantially the same magnetic state between the current pulses due to the magnetic hysteresis of the material.

In a further comparison, the valve of Figure 1 was operated with a nozzle bore having a length to diameter ratio of 10:1, 8:1, 5:1, 4:1 2:1 and 0.5:1 and at a drive current frequency of 2 kHz. At the 10:1 ratio, the pressure required to feed the ink through the bore to achieve a consistent printed dot size was about 10 Bar. However, such a pressure is too high for use with conventional drop on demand print heads and would have resulted in rupture of components. If the pressure was reduced to a more acceptable level, say about 3 Bar, the rate of flow of ink through the print head was insufficient to provide ink to form the droplets consistently so that the printed dots were of uneven size and there were missing dots where the valve had not been able to acquire ink from the reservoir.

Where the ratio was 8:1, the pressure required to feed the ink to the nozzle bore to achieve uniform printed dot size and quality was 5 Bar, which is at the upper extreme of operating capability of the components of a drop on demand printer.

Where the ratio was 5:1, 4:1 or 3:1, the printer operated

successfully at an ink pressure of 1 Bar and could print consistent dots at coil drive current frequencies of from less than 1 kHz to 7 kHz. As the length of the nozzle was reduced the quality of the printed dot improved marginally with the reduction in the l:d ratio. However, when the l:d ratio was reduced further from 3:1 to 2:1, there was a very much more marked improvement in the response of the valve to start up after a rest period. This improvement could not readily be explained.

Where the ratio was 0.5:1, the printer could not be operated, even at ink pressures of 0.1 Bar without causing spraying of the ink and the formation of multiple small dots as well as the desired main dots.

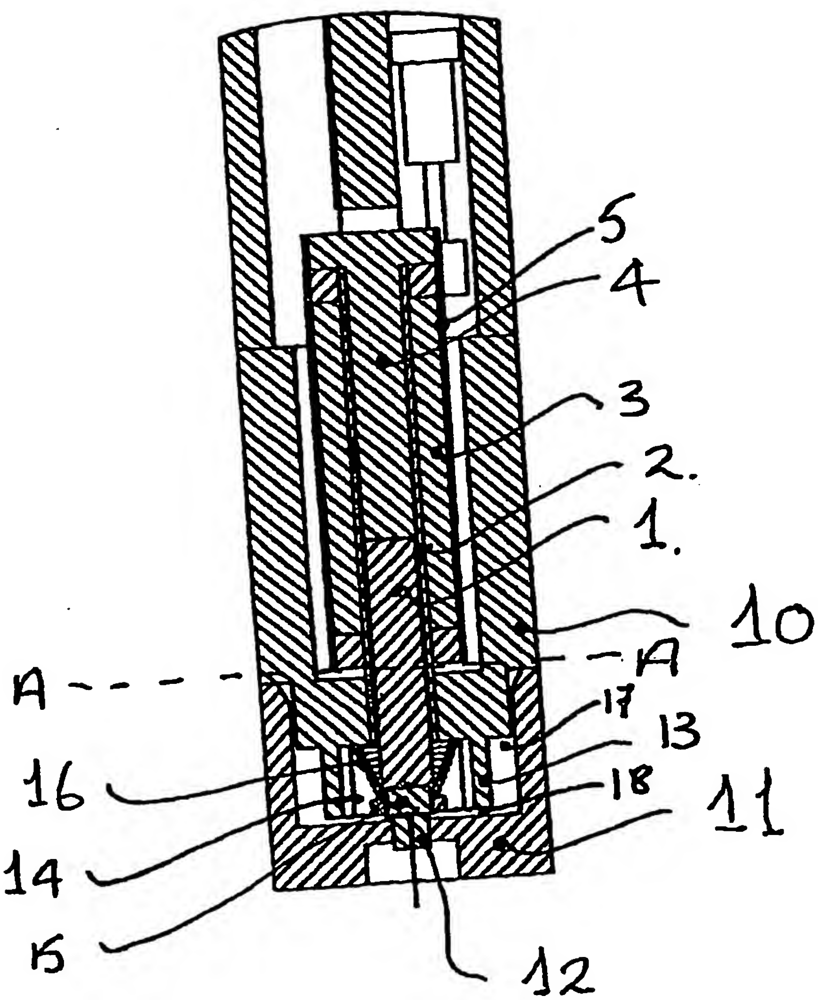

Figure 1

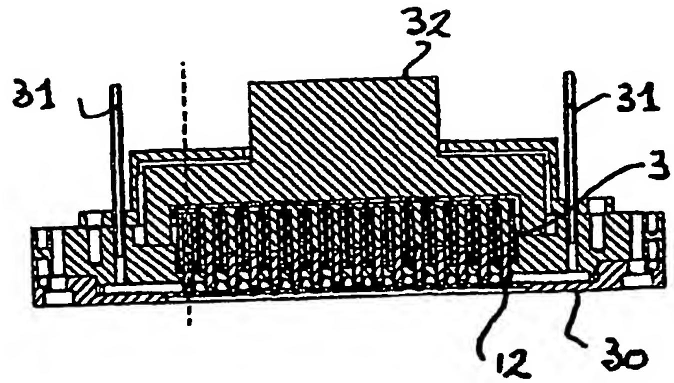

FIGURE 2.

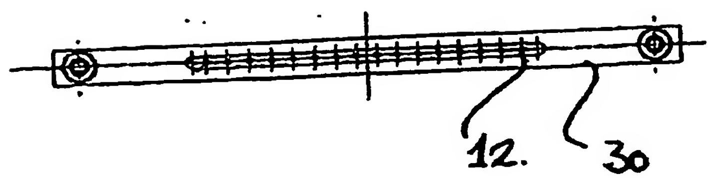

FIGURE 3.

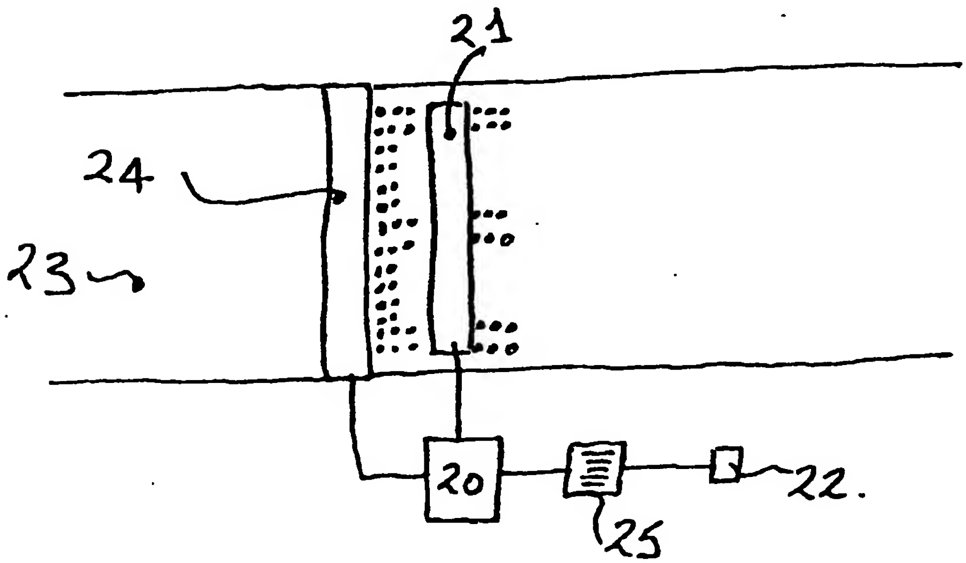

FIGURE 4

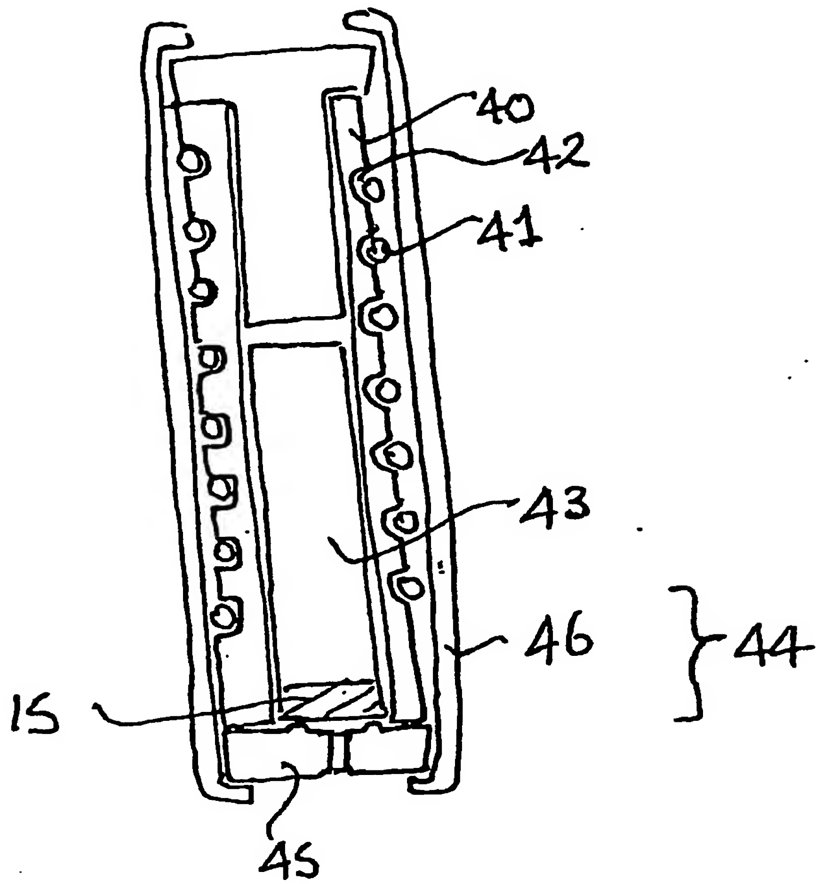

Figure 5.

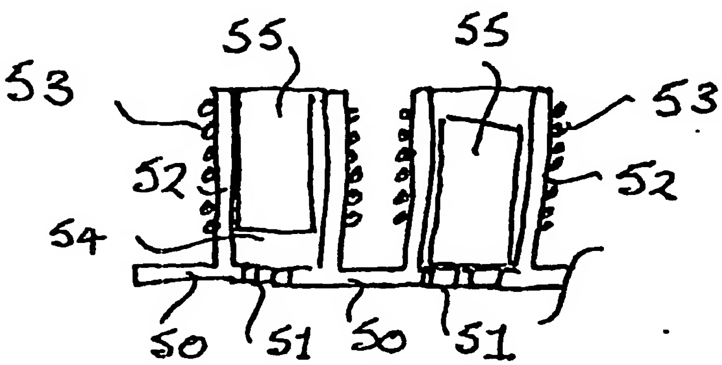

Figure 6

Figure 7.

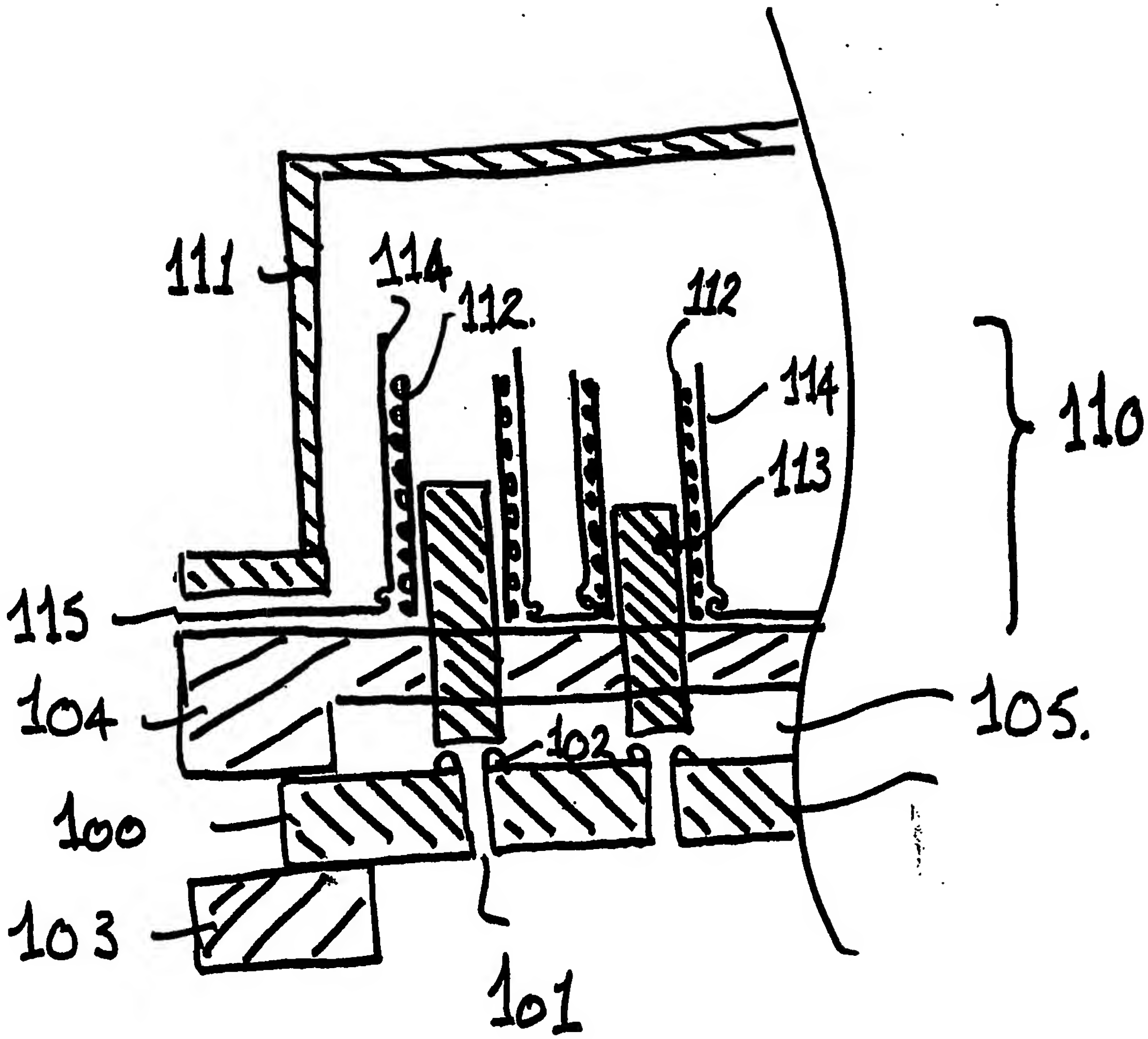

FIGURE 8